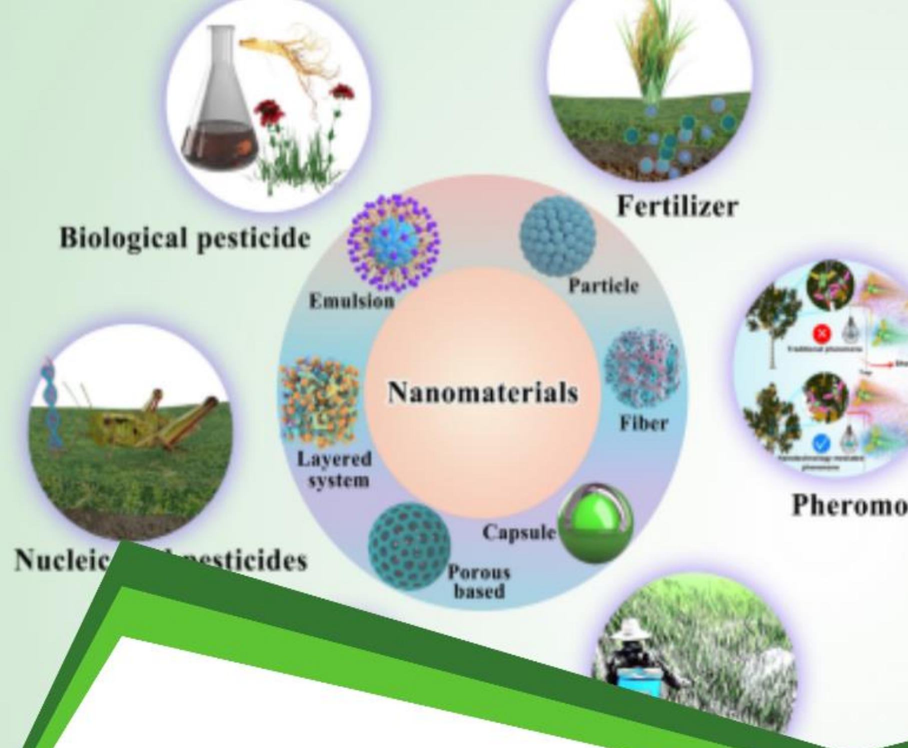

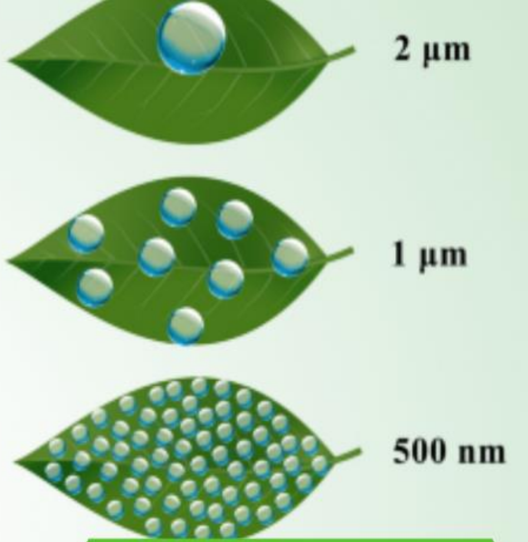

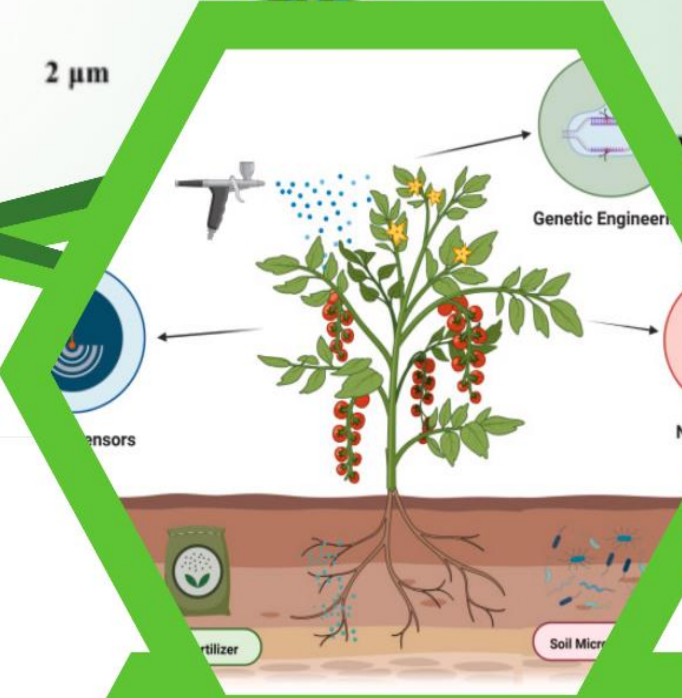

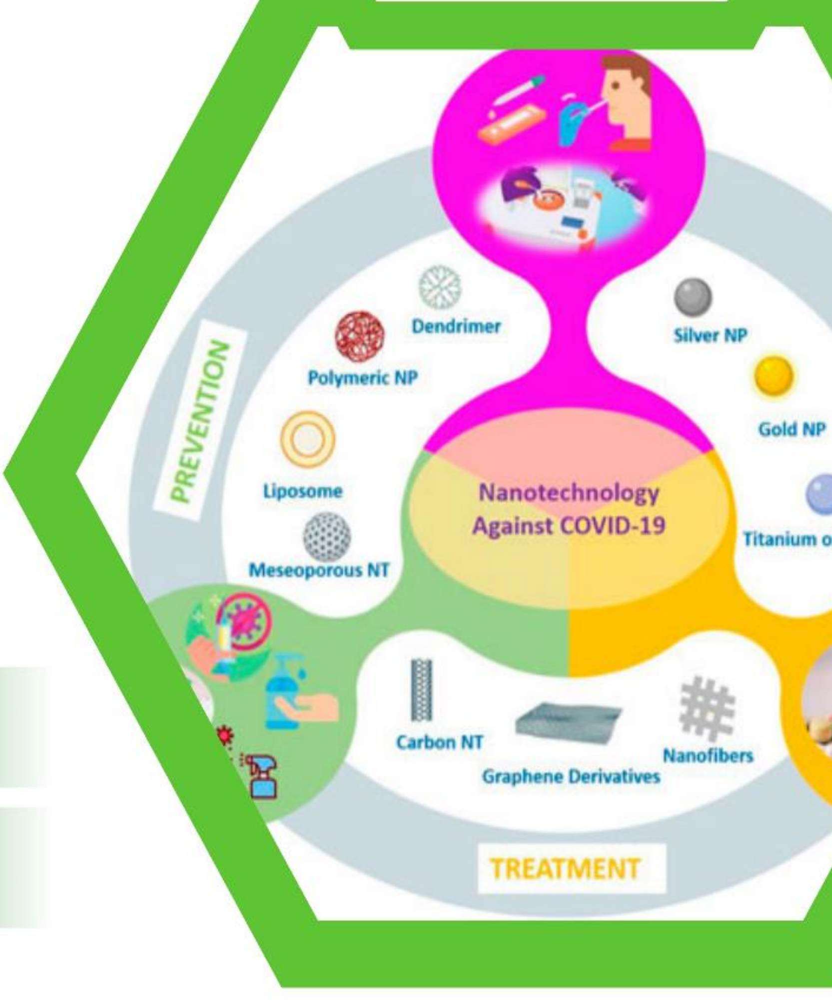

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Integration of Nanotechnological Innovation into Biotechnology: Advancements in Bioremediation and Biotechnology

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ABSTRACT

Nanotechnology has emerged as a groundbreaking approach in bioremediation and biotechnology, primarily because of its distinct characteristics at the nanoscale level. Nanomaterials such as zero-valent iron, various metal oxides, and carbon-based nanoparticles eliminate pollutants like heavy metals, synthetic dyes, and agricultural pesticides in bioremediation. These nanostructures boost microbial efficiency, accelerate contaminant degradation, and enhance the overall performance of phytoremediation methods. In biotechnology, the influence of nanotechnology has been significant, driving advancements in targeted drug delivery, biosensing, medical diagnostics, and genetic engineering. Nanocarriers allow for precise and regulated transportation of therapeutic agents, which reduces adverse effects and boosts treatment success. Nanoparticle-based biosensors offer rapid and highly sensitive detection of pathogens, toxins, and disease indicators. Furthermore, attaching enzymes to nanoparticles increases their operational stability and allows for repeated usage in industrial applications. Nanomaterials are also being studied as vectors for the safe and efficient transfer of genetic material into cells for gene therapy. Despite these benefits, there are still concerns regarding nanoparticle toxicity, ecological risks, and the economic feasibility of production. Future research should aim to create sustainable, biodegradable nanomaterials and establish robust safety regulations.

Keywords: Nanobioremediation, Biogenic nanoparticles, Nanomaterials toxicity, Enzyme immobilization, Bioprocess enhancement.

INTRODUCTION

Nanotechnology, which involves the manipulation and use of materials and systems at the nanometer scale (1–100 nm), has emerged as a groundbreaking discipline in modern science, especially within biotechnology and environmental research. The unique ability of nanomaterials to interact at molecular levels, along with their large surface area and high reactivity, positions them as powerful tools to tackle current challenges in areas such as pollution control, medical treatment, and industrial advancements. Over the past decade, the adoption of nanotechnology in both bioremediation and biotechnology has accelerated, offering innovative methods for environmental cleanup and biological improvement. In the field of bioremediation, nanotechnology plays a critical role in increasing the effectiveness of pollutant removal from contaminated ecosystems. Materials like zro-valent iron nanoparticles (nZVI), metal oxides (such as TiO_2 and ZnO), and carbon-based nanomaterials are extensively applied to break down or neutralize harmful substances, including toxic metals, agricultural chemicals, and persistent organic contaminants. These nanoparticles serve as either catalysts in chemical reactions or as facilitators for microbial degradation by improving pollutant bioavailability. For example, nZVI has proven effective in treating groundwater polluted with chlorinated solvents, where it transforms hazardous compounds into safer forms [1].

Additionally, when used in phytoremediation—the plant-based method for environmental cleanup—nanomaterials improve metal absorption and support plant resilience under stress, thereby increasing overall remediation outcomes. In biotechnology, nanotechnology has contributed remarkable advancements across diverse sectors such as healthcare, agriculture, biosensing, and bioprocessing. Nanocarriers are increasingly utilized to transport drugs and therapeutic agents precisely to targeted sites within the body, thus enhancing treatment specificity and reducing side effects. This is particularly vital for cancer treatment and genetic medicine. Furthermore, nanobiosensors made from materials like quantum dots, gold, or magnetic nanoparticles are enabling rapid and highly accurate detection of biomolecules, toxins, and pathogens. These sensors are vital for disease diagnosis, food safety, and environmental monitoring. A further impactful application of nanotechnology is seen in enzyme immobilization. By attaching enzymes to nanoparticles, their stability, activity, and operational lifespan can be significantly improved. This is beneficial in industries where enzymes are key to processes such as fermentation, food production, or wastewater treatment. Immobilized enzymes on nanostructures are more resistant to harsh conditions and can be reused multiple times, thus lowering operational costs [2].

However, even with these advancements, critical concerns must be addressed. Issues such as the toxicity of nanoparticles, their environmental impact, and the economic costs involved in their production pose barriers to widespread use. Future work must emphasize the development of eco-friendly, biodegradable nanomaterials and the establishment of strong regulatory frameworks for their safe application. To summarize, the combination of nanotechnology with bioremediation and biotechnology represents a forward-thinking strategy for addressing pressing environmental challenges. With ongoing innovation and responsible research, nanotechnology is set to become a cornerstone of sustainable scientific development [3].

Theoretical Framework and Methodological Approaches

1. Core Concepts

The interaction between nanomaterials and microorganisms, often referred to as nanomaterial–microbe synergy, is a key driver in nanotechnology-assisted bioremediation. At the nanoscale, these materials can function as adsorptive supports, concentrating contaminants near microbial cells; as electron donors or acceptors, facilitating redox reactions; or as carriers, stabilizing and delivering biocatalysts. Such interactions can markedly increase biodegradation rates—for instance, the integration of nanoscale zero-valent iron (nZVI) with dechlorinating bacteria has been shown to accelerate the removal of chlorinated solvents [4].

Another important mechanism is surface-mediated catalysis and adsorption. Nanoparticles possess an exceptionally high surface-to-volume ratio, providing abundant reactive sites for pollutant adsorption or catalytic transformation. Metal oxide nanoparticles like TiO_2 can initiate photocatalytic reactions under light exposure, generating reactive oxygen species capable of decomposing persistent organic contaminants [5]. Similarly, iron-based nanoparticles can trigger Fenton-like oxidation processes, converting hazardous compounds into less toxic by-products.

Sustainable nanoparticle production is increasingly achieved via biogenic (green) synthesis, which uses microorganisms or plant extracts as reducing and stabilizing agents. This method not only minimizes hazardous chemical use but also produces particles with higher biocompatibility. A notable example is the synthesis of silver nanoparticles from Azadirachta indica (neem) extract, which exhibit both antimicrobial properties and catalytic activity in pollutant breakdown [6].

Functionalization and targeting can further optimize nanoparticle performance. Techniques such as polymer coating, ligand attachment, or composite integration enhance particle stability, prevent aggregation, and improve selectivity for specific contaminants. For example, functionalized nZVI retains its reactivity in groundwater for longer durations compared to its unmodified form [7].

2. Common Materials and Properties

Nanoscale zero-valent iron (nZVI): Highly effective in reducing heavy metals and degrading halogenated organics due to its strong reductive potential [8].

Metal and metal oxide nanoparticles: Ag, Au, TiO_2, and ZnO are photocatalysts and antimicrobial agents, making them suitable for water purification applications.

Carbon-based nanomaterials: Materials such as carbon nanotubes and graphene offer large surface areas and high conductivity, facilitating both adsorption and electron transfer in microbially mediated reactions.

Nanocomposites and metal–organic frameworks (MOFs): Provide adjustable porosity and active sites, enabling targeted adsorption and catalytic processes.

Biogenic nanoparticles: Produced by microorganisms or plants, combining environmentally friendly synthesis with functional surface chemistry to improve pollutant interactions.

REVIEW OF LITERATURE

Advancement of Nanotechnology in Bioremediation and Biotechnology (2015-2025)

2015–2016: Advancements in nZVI for Environmental Cleanup

During this period, nanoscale zero-valent iron (nZVI) emerged as a leading in-situ technology for treating heavy metals and chlorinated compounds in contaminated soils and groundwater [9].

Researchers developed surface-engineered and composite forms of nZVI—incorporating polymers, minerals, or surfactants—to enhance particle stability, improve subsurface mobility, and boost reactivity toward pollutants [10].

2017–2018: Growth of Magnetic Nanoparticles and Nanozyme Applications

Magnetic nanoparticles, particularly Fe_3O_4-based systems, gained traction for their ability to remove contaminants and be magnetically recovered for reuse [11].

Simultaneously, nanozymes—nanostructures with enzyme-mimicking catalytic properties—emerged as stable, economical, and effective alternatives to natural enzymes for pollutant breakdown and biosensing tasks [12].

2019–2020: Merging Nanotechnology with Biological Processes

Research progressed toward nano-bioremediation, integrating nanomaterials with microbial or plant-based systems to accelerate pollutant degradation by localizing contaminants near active biological sites [13].

Gold nanoparticle-based biosensors became critical tools during the COVID-19 pandemic, offering rapid, highly sensitive, and portable pathogen detection [14].

2021–2022: Innovations in Nanocarrier Gene Delivery and Eco-Friendly Synthesis
Lipid nanoparticles (LNPs) underwent refinement for delivering CRISPR/Cas systems and mRNA-based therapeutics, achieving improved encapsulation and tissue-specific targeting. Selective Organ Targeting (SORT) LNPs expanded delivery beyond the liver, increasing precision in gene therapy [15].
Green-synthesized nanomaterials, derived from biological resources, drew attention for their reduced environmental toxicity and suitability in sustainable remediation [16].

2023–2024: Breakthrough Photocatalysts and Real-World Deployment
Composite photocatalysts—such as ZnO–CdS–rGO and $LaFeO_3$–MoS_2—were developed with enhanced capabilities to degrade persistent organic pollutants efficiently [17].
This era also saw the scaling up of nanoremediation through pilot projects, with attention to regulatory standards, environmental safety, and lifecycle assessment for long-term sustainability [18].

2025 (Current): Hybrid Approaches and Circular Nanotechnology
Ongoing studies are testing integrated remediation systems that combine nanomaterials, genetically engineered microorganisms, and gene-editing tools for highly targeted contaminant removal.
Research priorities are shifting toward nanoparticle recovery and reuse, minimizing ecotoxicological risks, and enabling large-scale industrial and environmental deployment [19].

Mechanistic Roles of Nanotechnology in Bioremediation

1. Enhanced Adsorption and Sequestration

Due to their large surface-to-volume ratio and tunable surface functionalities, nanomaterials provide a multitude of active sites capable of efficiently binding contaminants. When coupled with microbial biofilms, these materials act as concentrators, drawing pollutants into close contact with microbial enzymes. This proximity accelerates the degradation of organic compounds and the immobilization of heavy metals. For example, carbon nanotube–biofilm composites have significantly improved pollutant removal efficiency in wastewater treatment systems [20].

2. Reductive and Oxidative Transformation

Nanoscale zero-valent iron (nZVI) and certain metal oxide nanoparticles can function as strong electron donors or catalytic agents for oxidative degradation processes. nZVI is particularly effective in reducing halogenated organic pollutants and toxic metal ions, transforming them into less harmful or immobilized forms that microbes can subsequently mineralize [21]. Similarly, iron oxide and TiO_2 nanoparticles can produce reactive oxygen species (ROS) through light activation or Fenton-like reactions, leading to the breakdown of persistent organic contaminants [22].

3. Electron Shuttling to Microbes

Electrically conductive nanomaterials—such as graphene, carbon nanotubes, and select metal oxides—enhance extracellular electron transfer (EET) between microorganisms and insoluble electron acceptors. This property is especially beneficial in anaerobic biodegradation processes and microbial fuel cell technologies, where improved EET significantly increases the metabolic activity of electroactive bacteria, thereby accelerating contaminant degradation rates.

4. Enzyme Stabilization and Immobilization

Nanostructured carriers can be employed to immobilize enzymes, including laccases, peroxidases, and hydrolases, which boosts their reusability, activity, and resilience under challenging environmental conditions. Immobilization on magnetic or mesoporous nanomaterials safeguards enzymes from denaturation and allows for efficient recovery from reaction systems. This strategy enhances cost-effectiveness and operational sustainability in large-scale bioremediation projects.

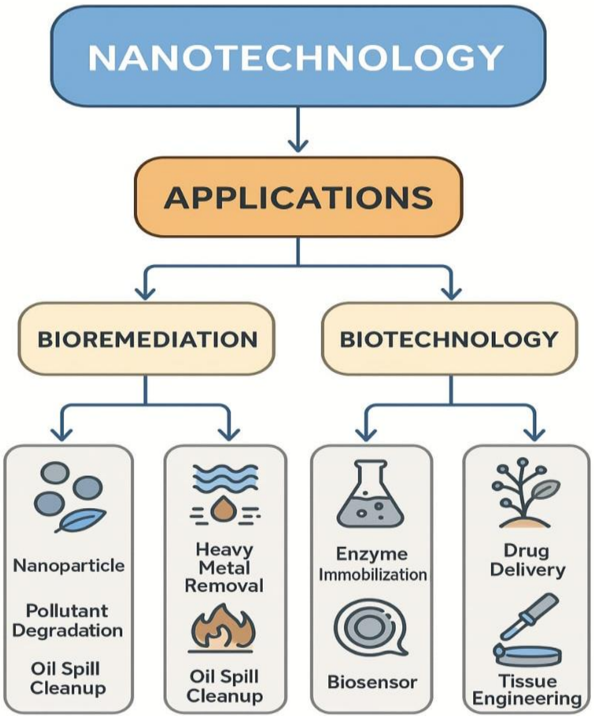

Figure 1: Role of Nanotechnology in Bioremediation.

Integration of Nanotechnological Innovation into Biotechnology

Nanotechnology has emerged as a pivotal element in modern biotechnology, offering unparalleled precision in manipulating biological systems at both molecular and cellular scales. This convergence—often referred to as *nanobiotechnology*—has unlocked innovative opportunities in diagnostics, therapeutics, agriculture, and industrial bioprocessing. In the field of medical biotechnology, nanoscale materials such as gold nanoparticles, liposomes, dendrimers, and quantum dots are utilized for site-specific drug delivery, early disease detection, and advanced imaging. For example, drug-loaded nanoparticles can preferentially accumulate in targeted tissues, thereby boosting treatment efficiency while reducing adverse effects. Likewise, nanostructured biosensors are capable of detecting biomarkers at extremely low concentrations, enabling fast and precise diagnostic outcomes [23].

Within industrial biotechnology, nanotechnology plays a crucial role in improving enzyme immobilization, bioseparation techniques, and fermentation efficiency. Nanostructured carriers enhance enzyme performance, stability, and reusability, which in turn reduces production costs. Additionally, nanomaterial-based delivery platforms have optimized genetic engineering tools, such as CRISPR-Cas9, by improving gene transfer rates and minimizing unintended modifications [24]

In agricultural biotechnology, nanotechnology-driven products like nanopesticides, nano-fertilizers, and nanosensors provide eco-friendly solutions to enhance crop yields and manage plant diseases. These technologies promote reduced chemical consumption, lower environmental hazards, and support precision farming approaches [25].

The fusion of nanotechnology with biotechnology is not simply additive but synergistic, generating breakthroughs that tackle critical issues in healthcare, sustainable agriculture, and environmental protection—firmly establishing nanobiotechnology as a transformative discipline of the modern era.

Safety, Ethics, and Regulatory Framework in Nanotechnology Applications

Nanotechnology holds immense promise for advancing both bioremediation and biotechnology; however, its application in environmental and industrial contexts raises essential concerns around safety, ethics, and governance.

Safety Considerations

Engineered nanoparticles possess the ability to penetrate biological membranes, interact with intracellular structures, and potentially cause oxidative stress, cytotoxicity, or genetic damage. In both aquatic and terrestrial environments, their high persistence and mobility can lead to unintentional exposure of non-target organisms [26]. Furthermore, the possibility of bioaccumulation and movement through food chains underscores the need for comprehensive, long-term ecotoxicological evaluations before they are deployed in natural systems.

Ethical Concern

Applying nanotechnology in biotechnology also introduces ethical challenges related to protecting ecological balance, safeguarding biodiversity, and upholding responsibilities to future generations. Releasing nanoparticles into the environment without fully understanding their long-term fate could lead to irreversible harm, raising issues regarding the precautionary principle and obtaining informed consent from communities impacted by such interventions. Equity concerns also emerge, as access to advanced nanotechnology-based solutions may remain uneven between developed and developing regions [27].

Regulatory Framework

On a global scale, the regulation of nanotechnology is still evolving and often inconsistent. The European Union implements the REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) regulation for certain nanomaterials, while the U.S. Environmental Protection Agency manages them under the Toxic Substances Control Act. However, many of these measures adapt pre-existing chemical laws rather than establishing nanoparticle-specific rules, leading to gaps in standardized risk assessment approaches. Developing uniform protocols for nanoparticle characterization, toxicity evaluation, and environmental monitoring is vital for safe commercialization [28].

To ensure responsible progress, integrating evidence-based regulation, ethical oversight, and open risk communication is essential for building public trust and supporting sustainable nanotechnology development in environmental and biotechnological sectors.

Challenges and Limitations of Nanotechnology in Bioremediation and Biotechnology

Nanotechnology offers significant promise in both bioremediation and biotechnology, but its widespread application is hindered by various scientific, technical, and socio-economic challenges.

1. Technical and Scientific Constraints

A major hurdle is the limited understanding of how nanoparticles behave and interact within complex biological and environmental systems. Differences in particle size, surface charge, and reactivity can alter their mobility, stability, and transformation in soils and aquatic environments. Furthermore, translating laboratory results into effective large-scale applications remains difficult, as real-world environmental variability often reduces the efficiency observed under controlled conditions.

2. Environmental and Health Risks

Due to their small size, nanoparticles can penetrate biological membranes, potentially inducing oxidative stress, DNA damage, or immune system disturbances. Their durability in the environment raises concerns about long-term bioaccumulation and movement through food chains [29]. Without comprehensive life-cycle assessments, introducing nanomaterials could lead to unforeseen effects, particularly in vulnerable ecosystems.

3. Economic and Infrastructure Barriers

High production costs for engineered nanomaterials, along with the requirement for specialized facilities and equipment, limit their availability in resource-limited regions. Additionally, the absence of uniform methods for nanoparticle characterization and toxicity evaluation complicates both regulatory approval and international trade.

4. Regulatory and Public Acceptance Issues

Many regulatory systems are still adapting and often rely on conventional chemical safety standards, which may not fully address nano-specific risks. Public apprehension—driven by environmental and ethical concerns—can also slow technological adoption. Building public trust will require transparent communication and the active involvement of stakeholders.

Overcoming these limitations will depend on cross-disciplinary collaboration, enhanced risk evaluation methods, and the development of affordable, scalable nanomaterial production processes. Only through such measures can nanotechnology realize its full potential in sustainable environmental and biotechnological advancements.

Future scope of advancement of nanotechnology in bioremediation and biotechnology

1. Green and Sustainable Nanoparticle Synthesis

Upcoming advancements in nanotechnology will emphasize eco-friendly synthesis techniques that utilize plant extracts, microbial systems, and biodegradable polymers. Such green approaches aim to reduce toxic by-products, lower overall toxicity, and enhance environmental safety—ensuring the long-term viability of nanomaterials in biotechnology and bioremediation [30].

2. Nano–Synthetic Biology Integration

The merging of nanotechnology with synthetic biology has the potential to create advanced bio-hybrid systems for pollutant removal, biosensing, and targeted drug delivery. Microorganisms engineered in combination with nanomaterials could be tailored to break down persistent pollutants more effectively while preserving ecological stability [31].

3. Advanced Nanosensors for Real-Time Monitoring

Future nanosensors are expected to provide on-site, real-time data on contaminant levels and microbial performance during bioremediation. When integrated with catalytic nanomaterials, these sensors could trigger rapid corrective actions in polluted environments, thereby increasing the efficiency and precision of remediation processes [32].

4. Artificial Intelligence in Nanotechnology Design

Integrating AI and machine learning into nanotechnology research will allow predictive modeling of nanoparticle interactions with specific contaminants. This data-driven approach can optimize nanoparticle properties before synthesis, speeding up development, lowering research costs, and minimizing reliance on trial-and-error methods.

5. Strengthening Global Regulatory Frameworks

With the expansion of nanotechnology applications, the creation of unified and robust international safety regulations will be crucial. These frameworks should include standardized toxicity evaluations, comprehensive lifecycle assessments, and safe disposal practices to safeguard human health, protect the environment, and maintain public confidence in nanotechnology solutions.

Global Economic Benefits of the Advancement of Nanotechnology in Bioremediation and Biotechnology

1. Cost-Effective Environmental Remediation

Advanced nanomaterials like zero-valent iron (nZVI) and titanium dioxide (TiO_2) can degrade pollutants more rapidly and in smaller quantities compared to traditional remediation techniques. Their higher efficiency leads to reduced operational expenses in processes such as industrial wastewater treatment and oil spill management, making large-scale cleanup projects more financially feasible [33].

2. Improved Resource Recovery

Nanotechnology-driven recovery systems enable the extraction of precious metals such as gold, silver, and copper from industrial waste streams and electronic waste. This approach promotes a circular economy by minimizing disposal needs while generating additional revenue sources for sectors like mining, electronics, and manufacturing [34].

3. Increased Agricultural Productivity

In agricultural biotechnology, nanotechnology facilitates targeted delivery of fertilizers, agrochemicals, and pesticides, enhancing crop productivity with reduced resource usage. Controlled-release nanocarriers minimize wastage and ensure precise application, increasing profitability for farmers, particularly in resource-limited regions [35].

4. Growth of Global Market Potential

The global nanotechnology market for environmental applications is witnessing rapid expansion, with forecasts predicting it will surpass USD 125 billion by 2030. Nations prioritizing nanotechnology research and development are positioned to gain a strong competitive edge in exporting nano-based goods, specialized services, and patented innovations.

5. Job Creation and Technological Growth

The integration of nanotechnology into industrial and environmental sectors supports the establishment of new industries, including nanomaterial fabrication and advanced environmental monitoring. This transition creates high-skilled employment opportunities, promotes innovation, and strengthens the technological backbone necessary for sustainable economic progress.

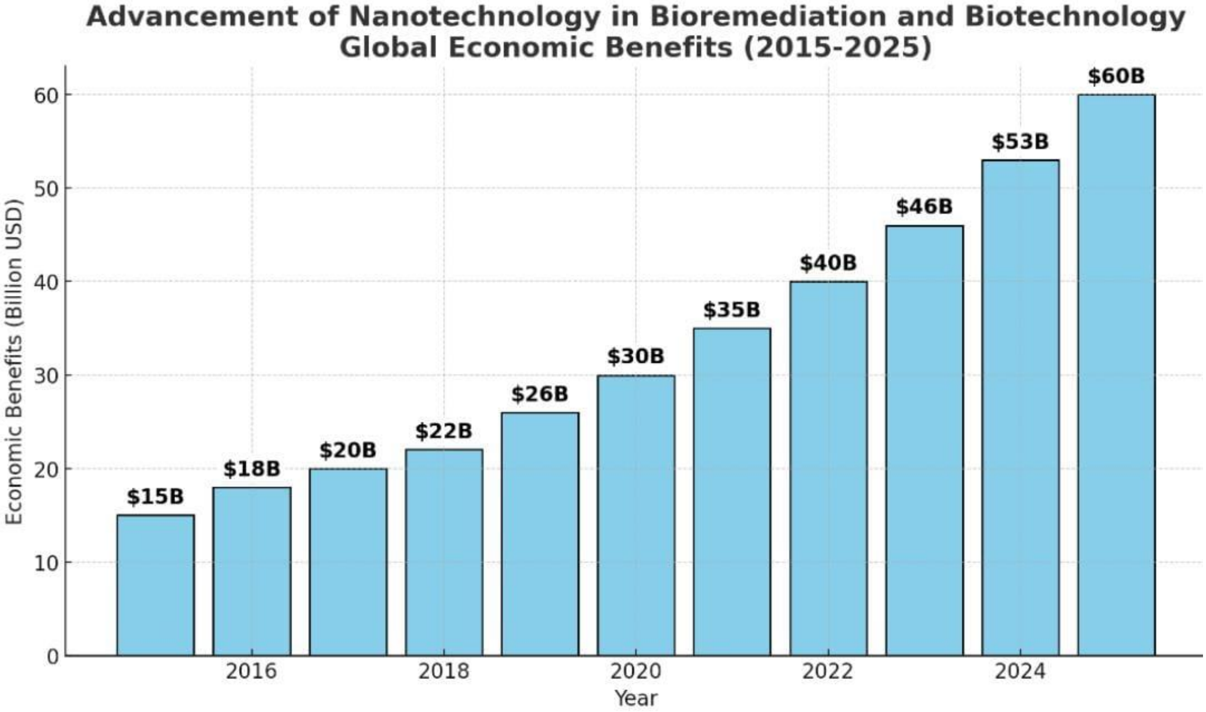

Figure 2: Yearly increase in Nanotechnology market size (USD Billion).

CONCLUSION

The rapid progress of nanotechnology in bioremediation and biotechnology marks a significant breakthrough in tackling critical environmental and industrial issues. Utilizing the exceptional physicochemical traits of nanomaterials—such as their large surface area, adjustable reactivity, and ability for precise delivery—researchers have developed advanced systems for pollutant removal, resource recovery, agricultural productivity improvement, and biomedical innovations. In bioremediation, nano-assisted techniques not only hasten the decomposition of hazardous compounds but also enable targeted, site-specific interventions, thereby lowering both costs and ecological disruption. In the biotechnology sector, nanoscale tools have enhanced precision drug delivery, gene editing capabilities, and biosensor performance, leading to better therapeutic outcomes and more accurate diagnostics. Moreover, the incorporation of nanotechnology into these fields stimulates economic development through the creation of emerging markets, job generation, and eco-friendly industrial operations. However, addressing ethical issues, ensuring environmental safety, and implementing robust regulations remain essential for responsible deployment. Advancing this domain will require continued interdisciplinary efforts and global partnerships to fully realize its societal and economic potential while minimizing risks. With sustained innovation, nanotechnology is set to become a cornerstone in building a cleaner, healthier, and more sustainable world.

REFERENCES

1. Karn, B., Kuiken, T., & Otto, M. (2009). Nanotechnology and in situ remediation: A review of the benefits and potential risks. *Environmental Health Perspectives, 117*(12), 1823–1831.
2. Rai, M., Yadav, A., & Gade, A. (2012). Silver nanoparticles as a new generation of antimicrobials. *Biotechnology Advances, 30*(1), 76–83.
3. Bhattacharyya, A., Bhaumik, A., & Mondal, A. (2011). Nanotechnology: A new frontier in modern science. *Journal of Nanoscience and Nanotechnology, 11*(1), 1–10.
4. Zhao, X., et al. (2021). Coupling nanoscale zero-valent iron with dechlorinating bacteria for enhanced removal of chlorinated solvents. *Journal of Hazardous Materials, 402,* 123512.
5. Chong, M. N., Jin, B., Chow, C. W., & Saint, C. (2010). Recent developments in photocatalytic water treatment technology: A review. *Water Research, 44*(10), 2997–3027.
6. Iravani, S. (2011). Green synthesis of metal nanoparticles using plants. *Green Chemistry, 13*(10), 2638–2650.
7. Singh, R., et al. (2020). Functionalized nanoscale zero-valent iron for enhanced environmental remediation: A review. *Environmental Science and Pollution Research, 27*(29), 34714–34735.
8. Zhang, W. (2003). Nanoscale iron particles for environmental remediation: An overview. *Journal of Nanoparticle Research, 5*(3–4), 323–332.
9. Zou, Y., Wang, X., Khan, A., Wang, P., Liu, Y., Alsaedi, A., ... & Wang, X. (2016). Environmental remediation and application of nanoscale zero-valent iron and its composites for the removal of heavy metal ions: A review. *Environmental Science & Technology, 50*(14), 7290–7304.
10. He, F., & Zhao, D. (2016). Manipulating nZVI transport in subsurface environments with particle surface coatings: A review. *Journal of Hazardous Materials, 320,* 210–230.
11. Wu, J., Wang, X., Wang, Q., Lou, Z., Li, S., Zhu, Y., ... & Wei, H. (2019). Nanomaterials with enzyme-like characteristics (nanozymes): Next-generation artificial enzymes (II). *Chemical Society Reviews, 48*(4), 1004–1076
12. Huang, Y., Ren, J., & Qu, X. (2019). Nanozymes: Classification, catalytic mechanisms, activity regulation, and applications. *Chemical Reviews, 119*(6), 4357–4412.
13. Khan, S., Cao, Q., Zheng, Y., & Yang, P. (2019). A review on the application of nanomaterials in bioremediation of environmental pollutants. *Journal of Environmental Management, 241,* 178–188.
14. Qiu, G., Gai, Z., Tao, Y., Schmitt, J., Kullak-Ublick, G. A., & Wang, J. (2020). Dual-functional plasmonic photothermal biosensors for highly accurate severe acute respiratory syndrome coronavirus 2 detection. *ACS Nano, 14*(5), 5268–5277.
15. Patil, S., Singh, N., & Sinha, S. (2021). Lipid nanoparticles in gene therapy: Current status and future directions. *Molecules, 26*(22), 6806.
16. Yadav, A., Singh, S., & Kumar, S. (2022). Green synthesis of nanomaterials for environmental remediation: Recent advances and prospects. *Environmental Nanotechnology, Monitoring & Management, 18,* 100701.
17. Singh, R., Sharma, A., & Bhardwaj, R. (2023). Advances in photocatalytic nanocomposites for the degradation of persistent organic pollutants. *Journal of Nanobiotechnology, 21,* 87.
18. Rahman, M., Alam, M., & Karim, M. (2024). Nanoremediation: Recent advances, challenges, and future perspectives. *Environmental Science and Pollution Research, 31*(15), 20356–20374.
19. Zhang, L., et al. (2022). *Science of the Total Environment, 812,* 151455.
20. Wang, H., et al. (2020). *Biotechnology Advances, 39,* 107463.
21. Singh, R., et al. (2021). *Journal of Environmental Chemical Engineering, 9*(4), 105498.

22. Mueller, N. C., et al. (2012). *Environmental Science & Technology, 46*(19), 11014–11023.
23. Rai, M., et al. (2018). Nanotechnology in biotechnology: Progress, prospects, and challenges. *Applied Microbiology and Biotechnology, 102*(2), 577–593.
24. Patra, J. K., et al. (2018). Nano-based drug delivery systems: Recent developments and prospects. *Journal of Nanobiotechnology, 16*, 71.
25. Perez-de-Luque, A. (2017). Interaction of nanomaterials with plants: What do we need for real applications in agriculture? *Frontiers in Environmental Science, 5*, 12.
26. Bhattacharyya, A., Bhaumik, A., & Mondal, A. (2011). Nanotechnology: A new frontier in modern science. *Journal of Nanoscience and Nanotechnology, 11*(1), 1–10.
27. Jain, K. K. (2008). Nanomedicine: Application of nanobiotechnology in medical practice. *Nanomedicine, 3*(4), 471–473.
28. Roco, M. C. (2003). Nanotechnology: Convergence with modern biology and medicine. *Current Opinion in Biotechnology, 14*(3), 337–346.
29. Karn, B., Kuiken, T., & Otto, M. (2009). Nanotechnology and in situ remediation: Benefits and potential risks. *Environmental Health Perspectives*, *117*(12), 1823–1831.
30. Iravani, S. (2011). Green synthesis of metal nanoparticles using plants. *Green Chemistry, 13*(10), 2638–2650.
31. Zhou, Y., Kong, Y., Kundu, S., Cirillo, J. D., & Liang, H. (2018). Antibacterial activities of gold and silver nanoparticles against *Escherichia coli* and *Bacillus Calmette–Guérin*. *Journal of Nanobiotechnology, 16*, 1–8.
32. Singh, R., Kumar, A., & Umar, A. (2021). Nanosensors for environmental monitoring and remediation. *Environmental Chemistry Letters*, *19*(2), 1295–1324.
33. Karn, B., Kuiken, T., & Otto, M. (2009). Nanotechnology and in situ remediation: A review of the benefits and potential risks. *Environmental Health Perspectives, 117*(12), 1823–1831.
34. Mudhoo, A., Sharma, S. K., Garg, V. K., & Tseng, C. H. (2011). Nanotechnology: A new paradigm for wastewater treatment. *Critical Reviews in Environmental Science and Technology, 41*(23), 2179–2210.
35. Rai, M., Ingle, A. P., Birla, S., Yadav, A., & Santos, C. A. (2015). Strategic role of nanotechnology in fertilizers: Potential and limitations. *Nanotechnology Reviews, 4*(1), 1–15.

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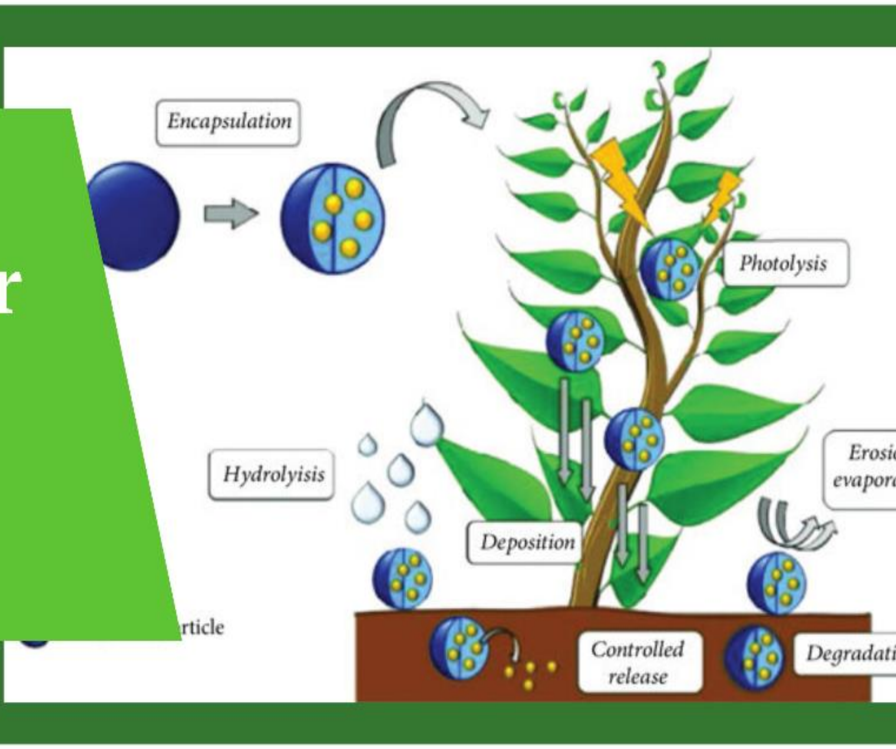

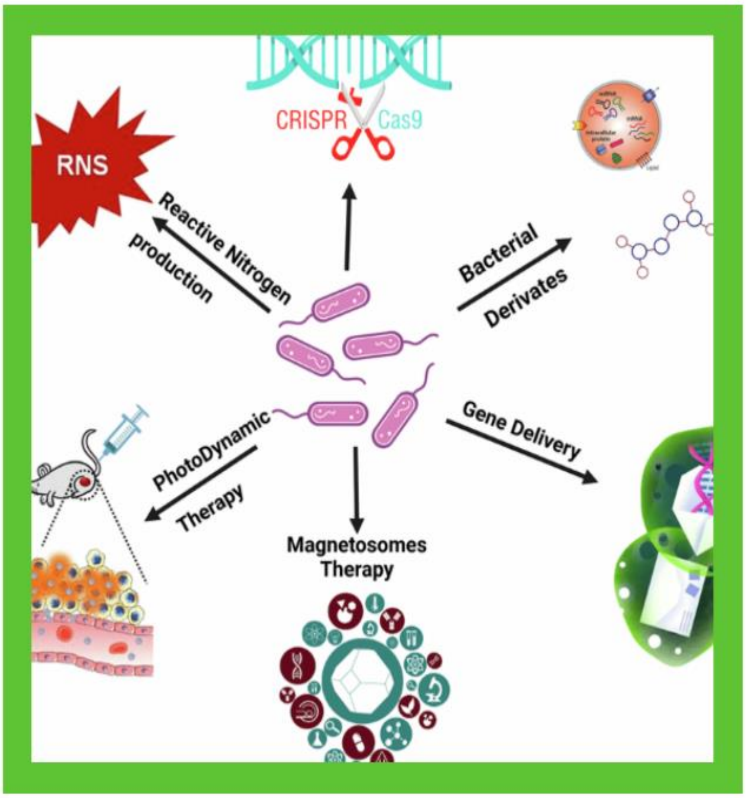

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